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Title: A critical analysis of regulated river ecosystem responses to managed environmental flows from reservoirs.

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Summary

1. The flow regime of a river is fundamental in determining its ecological characteristics. Impoundment of rivers has been documented to severely impact the natural flow regime, resulting in abiotic and biotic changes in downstream ecosystems. Contemporary water legislation is driving increasing concern among environmentalists and water resource managers with respect to how these impacts can be mitigated. This has stimulated research aimed at assessing the relationship between reservoir outflow modification (i.e. managed environmental flows) and downstream ecosystem responses.

2. We carried out a critical review and synthesis of the global literature concerning post-impoundment reservoir outflow modification and associated downstream biotic and abiotic responses. Seventy- six studies published between 1981 and 2012 were analysed. In contrast to previous studies of this subject, we systematically assessed the methodological quality of research to identify strengths and weaknesses of the approaches. We also undertook a novel quantification of ecosystem responses to flow modification, thus enabling identification of priorities for future research.

3. We identified that: (i) there was a research bias towards North American and Western European studies; (ii) the majority of studies reported changes in flow magnitude (e.g. artificial floods) and primarily focused on traditionally monitored ecological groups (e.g. fish); (iii) relationships between flow, biota (e.g. macroinvertebrates) and water quality (e.g. electrical conductivity and suspended solids concentration) were evident, demonstrating the potential for managed environmental flows to manipulate river ecosystems; (iv) site-specific factors (e.g. location, climate) are likely to be important as some ecosystem responses were inconsistent between studies

(e.g. fish movement in response to increases in flow magnitude); and (v) quality of study design, methodological and analytical techniques varied, and these factors may have contributed to the reported variability of ecosystem response.

4. To advance scientific understanding and guide future management of regulated flow regimes, we highlight a pressing need for: (i) diversification of study locations as well as flow modification and ecosystem response types assessed; (ii) a focus on understanding flow–ecosystem response relationships at regional scales; (iii) further quantitative studies to enable robust statistical analyses in future meta-analyses; and (iv) robust monitoring of flow experiments and the use of contemporary statistical techniques to extract maximum knowledge from ecological response data.

Introduction

The flow regime of a river is fundamental in determining its ecological characteristics (Power et al., 1995; Poff et al., 1997; Bunn & Arthington, 2002; Olden & Poff, 2003; Allan & Castillo, 1995; Naiman et al., 2008). Flow influences the abundance and distribution of lotic species (Allan & Castillo, 1995) both indirectly through physical habitat modification and directly through stimulation of biotic responses (Bunn & Arthington, 2002; Milner et al., 2013) [e.g. movement (James, Dewson & Death, 2008) and spawning (Gorski et al., 2010)]. The natural flow regime paradigm stresses that the natural characteristics of a flow regime are critical in maintaining ecological integrity (Poff et al., 1997), as the two are intrinsically linked having evolved together over time (Lytle & Poff, 2004). Ecological integrity is increasingly the focus of contemporary freshwater legislation (e.g. Clean Water Act, 2002; EU Water Framework Directive (EU WFD) (EC, 2000); Water Act, 2007), stimulating a desire to identify and understand river flow–ecosystem response relationships. This understanding is crucial for effective management of freshwater ecosystems (Tharme, 2003; Olden & Naiman, 2010; Shafroth et al., 2010; Rolls & Arthington, 2014) which is recognised as one of civilisation’s greatest contemporary challenges (Palmer et al., 2004; Vorosmarty et al., 2010; Naiman & Dudgeon, 2011).

River impoundment has been documented to severely impact characteristics of the natural flow regime, primarily through the reduction and redistribution of flow throughout time (Petts, 1984; Higgs & Petts, 1988; Nilsson et al., 2005). Globally, these impacts have been well documented; for example, Petts (1984) stated that mean annual discharge can be reduced by up to 80%, seasonal flow variability can be reduced, and the timing of annual extremes in flow can be altered. Annual peak discharges can be reduced by up to 90%, in some cases (Graf, 2006). General modifications of natural flow regime characteristics (including physicochemical modifications) have been associated with impacts to downstream ecosystems. Poff & Zimmerman (2010) found that 92% of studies reported reductions in ecological metrics in response to all anthropogenic flow modifications. Specifically, impacts to morphology (e.g. Petts & Pratts, 1983; Petts, Armitage & Castella, 1993; Sear, 1995; Shields, Simon & Steffen, 2000; Petts & Gurnell, 2005; Wellmeyer, Slattery & Phillips, 2005 and Xu et al., 2006), water quality (temperature: Baxter, 1977; Petts, 1984; Todd et al., 2005; Olden & Naiman, 2010; dissolved metal concentrations: Petts, 1984 and oxygen: e.g. Lutz, 1995) and biota, including primary producers (e.g. Jones & Barrington, 1985), macrophytes (e.g. Garcia De Jalon, Sanchez & Camargo, 1994 and Bernez et al., 2004), macroinvertebrates (e.g. Englund & Malmqvist, 1996; Growns & Growns, 2001 and Gillespie, Brown & Kay, 2014) and fish (e.g. Baran et al., 1995; Linnik et al., 1998 and Korman, Wiele & Torizzo, 2004) have been observed as a result of river impoundment. A drive to mitigate these impacts through reservoir outflow modification has recently been stimulated. These interventions are commonly described as 'environmental flows', and it is clear that their implementation will be vital to meet the aims of contemporary legislation [e.g. the Australian National Water Initiative (Connell & Grafton, 2008) and the EU WFD (Acreman & Ferguson, 2010)].

Environmental flows have been defined as 'the quantity, timing, duration, frequency and quality of water flows required to sustain fresh water, estuarine and near-shore ecosystems and the human livelihoods and well-being that depend on them' (Acreman & Ferguson, 2010, p. 32). More specifically, Acreman et al. (2009, p. 15) suggested that environmental flows should 'be based on ecological requirements of different communities/ species/life stages, which may vary within and between rivers even for the same biological elements or communities'. It is clear that to define environmental flows for regulated rivers, identification of cause–response relationships between flow modification and ecosystem response variables must be achieved (Shafroth et al., 2010). Such relationships have been hypothesised (Poff et al., 2010), but a synthesis of the global literature offers the potential to identify and quantify them.

Poff & Zimmerman (2010) have analysed the global literature on the ecological effects of altered flow regimes (often as a consequence of water storage in dams and water release patterns downstream). However, to date, no study has attempted to identify general relationships between flow modification interventions (e.g. artificial floods and other types of environmental flows) and ecological responses from the global literature.

A systematic synthesis of the global literature would allow for an evaluation of abiotic and biotic responses to managed environmental flows and facilitate identification of prominent knowledge gaps and prioritisation of future research agendas. Such insights and guidance would be useful given the relatively early stage of development and growing importance of the science of environmental flows (Tharme, 2003; Reich et al., 2010; Davies et al., 2014). It was envisaged that our study would build on recent reviews concerning the impacts of managed environmental flows (i.e. Konrad et al., 2011; Olden et al., 2014). Konrad et al. (2011) drew on case studies to identify challenges surrounding flow experimentation and proposed key principles to attain success in future flow experiments. Olden et al. (2014) then objectively catalogued and evaluated in broad terms the success of flow experiments globally. We propose that the next logical step should be an attempt to generalise flow modification– ecological response relationships from the literature and evaluate the quality of data underpinning these relationships. Thus, our study aims were to identify downstream ecosystem responses to managed environmental flows, quantify flow–response relationships and evaluate current research methods and study designs to prioritise and enhance future research agendas.

Methods

Literature search

Relevant published literature was located through computerised searches of ISI Web of Knowledge which includes the following databases: Web of Science (1990– present), BIOSYS Citation Index (1969–present), BIOSYS Previews (1969–present), Data Citation Index (1900– present), MEDLINE (1950–present) and Journal Citation Reports. Table 1 lists the search terms used and number of results returned. All searches were undertaken in July 2012 by a single reviewer, and a total of 3,981 records were assessed for suitability through attainment of the following criteria: (i) reported primary data; (ii) assessed the impact of modification of the outflow regime of a reservoir; (iii) focused on impacts to instream ecosystems (biotic and abiotic elements) downstream of the reservoir; and (iv) were published in academic journals and had thus undergone peer review (cf. Olden et al. (2014) who also incorporated grey literature). The latter criterion was considered to be particularly important given our emphasis on data extraction and meta-analysis, because incorporation of data sets contained only in grey literature may inhibit any future reassessments due to restricted access for other authors.

Data extraction and quality assessment

First, the study location(s) (reservoir where flow modification was made) reported in each study were recorded and mapped to assess any spatial patterns or biases in the literature. Next, ecosystem responses to flow modification highlighted in each study were recorded and categorised as either biotic or abiotic. To specifically build on the work of Olden et al. (2014), biotic changes were assigned to either reduced, no change or increased response categories to allow for comparison of general trends (see Poff & Zimmerman, 2010). For example, increased macroinvertebrate diversity in response to flow modification was classified as an increased response. Likewise, a reduction in fish movement in response to flow modification was classified as reduced response. Additionally, biotic responses were split into native or non-native/ invasive groups where detail was given as each group may respond differently to flow modification (e.g. Cross et al., 2011). Abiotic responses were assigned to either change or no change categories as reductions or increases in abiotic parameters may be less comparable than for biotic responses (e.g. increased temperature and electrical conductivity (EC) are less likely to both be either ecologically ‘good’ or ‘bad’ than increased fish and macroinvertebrate abundance). To enable further breakdown of the types of responses researched, ecosystem responses were assigned to either: (i) fish; (ii) macroinvertebrates; (iii) macrophytes; (iv) primary producers (benthic); (v) morphology; (vi) water quality (including suspended sediment transport); and (vii) other categories.

Flow modification can often be classified as more than one type of response; for example, a flow modification from a reservoir may result in both an increase in magnitude and duration (Poff et al., 1997). Thus, to classify the type of flow modification each ecosystem response was associated with, we recorded the element of flow modification that was most emphasised by each study (following Poff & Zimmerman, 2010) using the characteristics listed as ecologically important by Poff et al. (1997). This approach differs to that of Olden et al. (2014) where flows were categorised based on management aim (e.g. operating regime; change in release mode). Ecosystem responses have been observed to vary depending on whether they arise as a result of a single, or a series of flow modifications (e.g. Uehlinger et al., 2003). Thus, to allow for separate analysis of these two modification types, ecosystem responses were further classified by whether they were reported as a result of a single or series of cumulative flow modifications. Ecosystem responses within each category were then synthesised, and commonly reported responses were tabulated. To allow for clear tabulation of results, a frequency of observation of at least four was selected to represent a ‘common’ observation.

In an attempt to produce quantitative relationships between reservoir outflow modification and ecosystem responses, first, we identified studies where a single flow modification and associated ecosystem response could be represented as percentage change. Of the 76 studies identified in the literature search, this was possible for 20; although some studies reported on more than one flow modification or ecosystem response, resulting in 119 observations of flow modification to ecosystem response being extracted in total. From initial analysis of data points, all observed ecosystem responses were a result of modification of flow magnitude. We thus defined percentage change for each flow modification using Equation 1, where x1 was pre-flow modification discharge magnitude and x2 was maximum (or minimum in the case of a reduction in magnitude) discharge magnitude of the flow modification. Equation 1 was also used for calculation of percentage change in ecosystem response, where x1 was pre-flow modification condition and x2 was either condition of maximum change from x1 (if sampling was undertaken during flow modification) or condition immediately after the flow modification (if sampling was undertaken after the flow modification). If possible, data were extracted from the text/tables and alternatively from figures. For response variables, where sampling was replicated, we used mean values and where non-significant responses were noted, we recorded percentage change as zero.

$$Percent\ change = \left(\frac{x2 - x1}{x1}\right) \times 100 \qquad \text{(Equation 1)}$$

To visualise flow–ecosystem response relationships, data points were organised by response type using the seven categories employed in qualitative data extraction and, where more than five data points reported on the same ecosystem response, plots of flow (percentage change) versus ecosystem response (percentage change) were created. For some ecosystem response types, visualisation revealed broadly linear relationships; the significance of these relationships was assessed using generalised linear models (GLM) with appropriate error distribution and link functions specified. Statistical analysis of fewer than 10 data points has been regarded as invalid (Roscoe, 1975); therefore, we carried out modelling only where a minimum of 10 data points had been extracted. Model validation was carried out to ensure approximate normal distribution and homogeneity of residuals. Significance of relationships was assessed through consideration of t-statistics and associated P values (e.g. Zuur et al., 2009). All visualisations and statistical analyses were undertaken in R v2.15.3 (2013), and relationships were considered significant at $P < 0.05$.

In their proposed principles for successful flow experiments, Konrad et al. (2011) cited study design and methodological approaches (e.g. control sites; replication) as important. To allow assessment of current research standards and to support recommendations to enhance future research strategies, we recorded: (i) the type(s) of sampling strategy used to detect ecosystem responses (quantitative, semi-quantitative or qualitative); (ii) whether randomisation or replication was applied in sampling designs; (iii) type(s) of control sites used (if any) (e.g. upstream of reservoir; nearby unregulated river); (iv) analytical approaches applied in each study; and (v) whether statistical power was reported.

Results

Most studies were located within North America and western Europe and a dearth of study locations was observed within equatorial regions, South America, north Africa, Asia and eastern Europe (Fig. 1A). Two study locations had notably high densities of work: Lake Powell (Glen Canyon Dam), U.S.A. and Lago di Livigno (Punt dal Gall Dam), Switzerland/ Italy (Fig. 1B).

Qualitative analysis of assembled datasets

The majority of studies (n = 69) focused on modified flow magnitude, with very few studies reporting on changed reservoir draw-off valve (n = 1), modified flow duration (n = 2), range (n = 2) and rate of change (n = 2) (Fig. 2). Studies reporting fish response were the most frequent (n = 28) and a relatively high number of studies reported on water quality and macroinvertebrate responses (n = 27 and 19, respectively). In contrast, few studies reported on macrophytes and primary producers (n = 3 and 12, respectively) (Fig. 3). Fifty-five and 21 studies reported ecosystem responses as a result of single or cumulative modifications in flow magnitude, respectively. However, only seven studies reported ecosystem responses associated with either rate of flow change, duration, range and draw-off depth from the reservoir (Table 2).

Numerous studies detailing ecosystem responses as a result of flow magnitude modification reported increased biotic responses (n = 35), although a similar number of studies reported decreased or no change in biotic response (n = 30 and 25, respectively). This trend was mirrored in ecosystem responses as a result of single flow magnitude modification; however, as a result of cumulative modifications in flow magnitude, the majority of studies reported decreased biotic responses (Table 2). Single modifications of flow magnitude were commonly reported to result in: (i) both increased and no change in fish movement (during flow modification); (ii) no change in fish abundance (after flow modification); and (iii) increased macroinvertebrate drift (during flow modification) and reduced macroinvertebrate density (after flow modification). Similarly, cumulative modifications of flow magnitude were associated with reduced macroinvertebrate density and, additionally, reduced periphyton mass (after flow modification).

The majority of studies reported changes in abiotic condition as a result of both single and cumulative modifications in flow magnitude. Common responses were identified as: (i) increased turbidity, suspended solids concentration (SSC) and bedload transport (during flow modification); (ii) reduced EC (during flow modification); and (iii) both no change and an increase in river temperature (during flow modification) (Table 2). Due to the limited number of studies reporting ecosystem changes as a result of other flow modification types (i.e. rate of flow change, duration, range and draw-off depth), generalisations of ecosystem response associated with these flow modification types could not be made.

Quantitative analysis of assembled datasets

Periphyton AFDM, chlorophyll–a, benthic macroinvertebrate density, seston AFDM and chlorophyll- a either decreased or showed no change after increased flow magnitude (Fig. 4a,c). Macroinvertebrate drift and concentrations of Escherichia coli either increased or did not change during increased flow magnitude (Fig. 4b,d). No clear trends in response direction or flow thresholds could be identified for any biotic response.

River EC was generally reduced during increased flow magnitude, and a general negative linear relationship was observed (Fig. 4e). Conversely, SSC generally increased during increased flow magnitude; however, this relationship was not significant ($t = \_1.50$, $P = 0.16$). No clear trend was observed for turbidity (Fig. 4f).

Quality assessment

Seventy-one, 14 and three studies used fully, semi-quantitative or qualitative methods, respectively, to assess ecosystem response to flow modification. Forty-seven studies described replication in sampling, whilst only 19 stated randomisation. Fully quantitative methods of fish and macrophyte assessment were used in fewer than 60% of cases, whereas over 85% of assessments were fully quantitative for all other ecosystem response types. Qualitative methods were only used for assessment of fish and macrophytes (6 and 33%, respectively). Whereas over 90% of assessments of water quality response were fully quantitative, fewer than 5% were stated as either replicated or randomised. Randomised sampling was stated in 50% of primary production assessments, whilst fewer than 25% of sampling designs for all other ecosystem responses were described as randomised. Over 50% of assessments of fish, macroinvertebrate and primary production response were defined as replicated, compared to fewer than 5% of assessments of water quality (Fig. 5).

Only 14 studies stated use of control sites, and of these, 10 used nearby unregulated rivers, five used controls upstream of the reservoir and one used a regulated (with unmodified flow) control (note: some studies used more than one control type). Thirty-four studies used descriptive or graphical methods to present results (i.e. no statistical testing), and 10 studies used correlation or regression between a metric of flow and ecosystem response. Twenty-eight studies assessed the impact of flow modification through comparison of ecosystem conditions either through time or between impact/control sites using simple one-way or two-way testing (e.g. Student’s t-test; Mann–Whitney U-test; ANOVA; Kruskall– Wallis test). Six studies used alternative methods: multiple linear/least linear squares/polynomial regression, general linear/additive/generalised linear mixed modelling. Only three studies tested site:period interaction terms as part of Before–After Control–Impact (BACI) (or derivations of) (Smith, 2002) designs, and only eight studies used analytical methods that took account of temporal autocorrelation. It was also identified that just two studies (Meissner, Muotka & Kananen, 2002; Rolls et al., 2011) noted statistical power of their methods.

Discussion

Spatial distribution of studies

The spatial distribution of studies found by this study was generally in agreement with Olden et al. (2014), further emphasising the requirement for research in areas where reservoir density is high and published research is currently limited (i.e. Eastern Europe, Asia, central eastern South America and Central and South Africa). This observed research bias should be taken into account when considering the global applicability and relevance of our findings.

Flow and ecosystem response types

Our finding that the majority of studies reported flow modification as an expression of change in magnitude was accordant with those of Poff & Zimmerman (2010) and Olden et al. (2014). We propose that this may be due to increased flow magnitude being the most perceptible element of change during flow modification, where changes in alternative flow elements (e.g. rate of change, timing) are more subtle, but still occur. Future publications reporting impacts of flow modification should take care to highlight all elements of hydrological change associated with measured ecosystem responses to enable scrutiny and integration of all flow–ecosystem relationships in subsequent reviews. Low flows are critical in determining ecosystem integrity in natural rivers (Poff et al., 1997; Ledger et al., 2013), but further analysis of our data set revealed that only one study reported on a reduction in flow magnitude (Saltveit et al., 2001; who found that fish stranding occurred as a result of rapid reductions in flow), whilst all other studies concerning changes in magnitude reported on increased flow magnitude. The impact of reduction in flow magnitude in regulated rivers is a key priority for future research as, for example, typical compensation flows in the U.K. were set, on average, over 22% higher than pre-impoundment natural low flows (Gustard, 1989). Given the importance of all trophic levels in sustaining freshwater ecological integrity (Parrish, Braun & Unnasch, 2003), the bias towards monitoring of traditional indicator taxa (e.g. fish) is a concern. This finding was also found by Olden et al. (2014), and there is therefore a clear need for diversification of monitoring strategies to cover less typically monitored taxa in future studies.

Qualitative and quantitative flow-ecosystem response relationships

A novel objective of this review, cf. preceding papers on the subject of flow experiments, was to extract, synthesise and evaluate ecosystem responses to reservoir outflow modification primarily designed to reduce/alleviate the impacts of flow regime alterations downstream from reservoirs. It was expected that this would reveal general flow–ecosystem response relationships for regulated rivers and highlight future research priorities, ultimately aiding advancement of the science of regulated river management.

Qualitative

The majority of flow magnitude modifications resulted in either increased or decreased ecosystem responses, demonstrating that reservoir flow magnitude modification is a potentially useful option to modify some ecological features in regulated rivers. However, no clear trend in biotic response to all, single and cumulative flow magnitude modifications was identified, suggesting the importance of site-specific factors. For example, it was found that in response to single increased flow magnitude events, seven studies reported no change in, and six studies reported increased fish movement (Table 2). These contradictory observations may be explained by a combination of factors, for example: the characteristics of the flow modification (e.g. percentage increase, rate of change); the characteristics of the fish monitored (e.g. species, size, flow preference); and additional abiotic factors such as season, antecedent flow conditions, instream habitat type, time since impoundment, time elapsed between flow modification and measurement of ecological responses. To enable a more robust analysis of these relationships, details on these potentially confounding factors must be considered in each study. We were unable to extract these data for this review, and future publications should therefore consider including detailed information on all potentially relevant factors.

Our qualitative analysis revealed some general trends in macroinvertebrate response: increased drift (during flow modification) and reduced benthic densities were results of both single and cumulative increases in flow magnitude (Table 2). Benthic macroinvertebrate density commonly increases post-impoundment (Petts, 1984), suggesting that increased flow magnitude events have potential to mitigate for this impact. Importantly though, some studies have noted a quick recovery from single flow magnitude modifications (e.g. Jakob, Robinson & Uehlinger, 2003) which suggests that one-off flow modification events may not be viable long-term mitigation methods. However, understanding of long-term responses of macroinvertebrates to reservoir flow modification is spatially limited (e.g. Robinson, Uehlinger & Monaghan, 2004; Mannes et al., 2008; Robinson & Uehlinger, 2008) and is a topic that requires further research globally.

We identified that the vast majority of flow magnitude modifications resulted in abiotic changes, specifically, increased turbidity, SSC and bedload transport (Table 2). This suggests that flow magnitude modification has potential for use in mitigation of the effects of impoundment such as reduced sediment transport (Petts, 1984; Petts & Gurnell, 2005). No studies were found that highlighted the long-term impact of flow magnitude modification on sediment transport as all sampling was undertaken during each event. We therefore recommend future research aims to assess how river sediment transport responds both during and after single and cumulative flow magnitude modifications.

Our qualitative analysis of physicochemical factors revealed that increased flow magnitude commonly resulted in reduced EC. Heterogeneity in concentrations of dissolved ions is typical in natural lotic systems (e.g. Glover & Johnson, 1974), thus increased flow magnitude events have the potential to mitigate reduced EC temporal variability observed post-impoundment (e.g. Palmer & O’Keeffe, 1990). It was also found that water temperature was commonly observed to decrease or not change as a result of increased flow magnitude; this is most likely due to site-specific climatic and reservoir characteristics and the vertical position of the draw-off valve used during flow modification. One study (Macdonald, Morrison & Patterson, 2012) found that draw-off level from the reservoir was a significant factor in determining downstream temperature. The potential for temperature modification through reservoir flow operation (see Olden & Naiman (2010) for discussion) is evident, which may be important given the crucial influence of temperature on biota in freshwater systems (Cummins, 1974; Beschta et al., 1987; Webb et al., 2008) and the significant impact of reservoirs on downstream thermal regimes (Petts, 1984; Dickson, Carrivick & Brown, 2012). Further research should be directed towards assessment of the relative importance of different flow modification types in controlling downstream temperature, especially the impact of reservoir draw-off level which, to date, has received little attention.

Quantitative

No clear trends were observed between flow magnitude modification and biotic responses, most likely reflecting minimal availability of data points and the importance of site-specific factors. For example, Robinson (2012) identified clear relationships between flood magnitude and biotic response for flow modification events for one river, but in our meta-analysis incorporating data from multiple locations, this relationship was not evident. Approximately linear relationships were found between percentage changes in flow magnitude modification and EC (negative relationship) and SSC (positive relationship), demonstrating the potential for manipulation of the magnitude of reservoir flow releases as a river management technique. The lack of statistical significance for the flow modification and SSC relationship indicates the potential importance of site-specific factors (e.g. local geology, characteristics of flow modification, antecedent flow). In accordance with Poff & Zimmerman (2010), no threshold flow changes (where abrupt changes in ecological response could be identified) were observed for these parameters, potentially due to the lack of thresholds, and/or the lack of quantitative data points with which to identify them (Poff & Zimmerman, 2010; Poff et al., 2010). Uncertainty around this issue warrants further research attention given the potential importance of such information for river managers (Richter et al., 2003).

Our review was carried out using a similar method to Poff & Zimmerman’s (2010) review of ecological response to flow regulation. The authors concluded that their focus on all river types and all types of modification (e.g. dam construction, irrigation and urbanisation leading to increased run-off) may have limited their ability to find general flow–ecosystem response relationships. Our review differed in that it focussed specifically on reservoir outflow modification post-impoundment (Table 3) in an attempt to address this limitation. However, similar to Poff & Zimmerman (2010), we found that our analysis was restricted by both the small number of data points and the limited information we were able to extract relating to potential confounding factors (Table 3). As development of flow–ecosystem response relationships in reservoir regulated rivers increases over time, we suggest that future research would benefit by analysing these relationships collectively between areas of similar climatological and geological characteristics, as these factors are expected to influence ecosystem response to flow modification (Arthington et al., 2006; Poff et al., 2010). This would further the development of smaller scale, regional or environment ‘type’ based relationships which are required for environmental flow setting frameworks such as ELOHA (Ecological Limits of Hydrological Alteration) (Poff et al., 2010) or the building block methodology (BBM) (King & Louw, 1998).

Quality assessment

Over 90% of studies used fully quantitative methods to assess at least one ecosystem response to flow modification, although method types varied by ecosystem response type. For example, fewer than 60% of methods were fully quantitative for assessment of fish and macrophytes. A propensity for semi-quantitative electric fishing techniques (32% of all fish response assessments) and the limited number of assessments of macrophytes (n = 3) explain this observation. Research has suggested that semi-quantitative methods of fish sampling to gauge abundance can be up to 95% accurate (Klein-Breteler, Raat & Grimm, 1990), thus the high proportion of semi-quantitative methods for assessment of fish response is not a major concern.

Johnson (2002) describes replication and randomisation as two ‘cornerstones’ of experimentation and states that they are integral to successful ecological research; yet, ecologists often commit replication errors (Hurlbert, 1984) and rarely select study areas or sampling locations randomly (Johnson, 2002). Our review identified similar trends, as 47 studies (62%) stated that replication was used in sampling, whilst only 19 (25%) stated randomisation was applied, but interestingly, the distribution of the use of these techniques was unequal among ecosystem response types. In particular, fewer than 5% of assessments of water quality responses were stated as either replicated or randomised, whereas all other ecosystem elements were stated as being assessed using either replicated or randomised methods in at least 30% of cases. No explanations of why replication or randomisation had not been carried out for water quality assessment were given. However, the approaches used may reflect consensus in the literature where replication (Hauer & Hill, 1996; USEPA, 2004) and randomisation (Hauer & Hill, 1996) are not highlighted as important in water quality monitoring. We have identified a lack of use of these ‘cornerstones’ and suggest that future research integrates both facets.

The majority of studies used one-way comparisons of sample periods (e.g. before/after flow modification) or between control/impact sites over sample periods. One of the limitations of these approaches is that they fail to take account of temporal autocorrelation (only eight studies (11%)

took temporal autocorrelation into account) and can result in less robust analysis (Zuur et al., 2009). BACI designs are recommended methodological frameworks for impact assessment of anthropologically driven disturbance events (Underwood, 1991) such as flow modifications from reservoirs. BACI designed experiments allow for significance testing of site:period interaction terms (see Underwood, 1991) which takes into account variation that is assumed to have occurred if the impact (e.g. flow modification) had not been undertaken. Nevertheless, only three studies used this approach and we suggest future researchers consider use of such a technique to assess impacts of reservoir flow modification. Selection of a control site is necessary when applying BACI approaches, but only 14studies (<20%) reported use of control sites. Within these studies, considerable variability in the ‘type’ of control site was identified. Currently, research is lacking as to which ‘type’ provides the most robust method. However, given that ideal control sites should be both independent of, but as similar as possible in abiotic and biotic characteristics to, the impacted site (e.g. McMahon, 2010), it is probable that an independent, regulated control site has the potential to act as the most effective control. Further research is required to test this hypothesis.

Reporting of statistical power in scientific research is important as it puts the finding of ‘no significant change’ or ‘no significant response’ in context and allows assessment of the likelihood of a type II error (Nakagawa, 2004). Just two studies noted the statistical power of their methods, and we therefore recommend reporting of this statistic in future studies to enable the assessment of false-negative errors. Such an assessment has the potential to reveal findings which require clarification and therefore merits further research.

Our literature search revealed inconsistent use of terms and keywords used to describe research concerning the impact of reservoir flow modification on downstream ecological conditions. To aid efficiency of future literature searches, we suggest all future literature concerning this topic includes the keywords ‘environmental flow’ and ‘reservoir’ where possible. The currently accepted definition of environmental flow is broad and encapsulates topics such as flow distribution in multicatchment water transfers, canals and wetlands (Dyson, Bergkap & Scanlon, 2003; Arthington, 2014), and thus, the inclusion of ‘reservoir’ will aid the search process.

Conclusion

This study has synthesised the global literature concerning managed environmental flows and the associated downstream river ecosystem response. We were able to recognise biases within both the location of studies and research topics. This study also identified qualitative and quantitative flow–

ecosystem response relationships. In particular, as a result of increased flow magnitude, macroinvertebrate density and drift were commonly identified to decrease and increase, respectively, and periphyton mass was commonly observed to decrease. Further, during increased flow magnitude, reduced EC and increased SSC, turbidity and bedload movement were commonly observed. However, our analyses were constrained by the limited number of quantitative data points available for analysis of specific flow–ecosystem response relationships. Nevertheless, from our synthesis, we were able to make a number of recommendations for future work (Table 3). We found that improvements in research design and analytical methodologies could be made through the implementation of contemporary techniques. Overall, our findings, together with the implementation of our recommendations for future research, have the potential to redirect and focus regulated river science and environmental flow management in a concerted and effective manner.

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Supporting information

Appendix 1: Studies used in literature review, including study ID, location and ecosystem response type reported by each study and a complete bibliography.

Figures

Figure 1 Location of the 76 studies considered within this review. B: Number of studies considered within this review at each location.

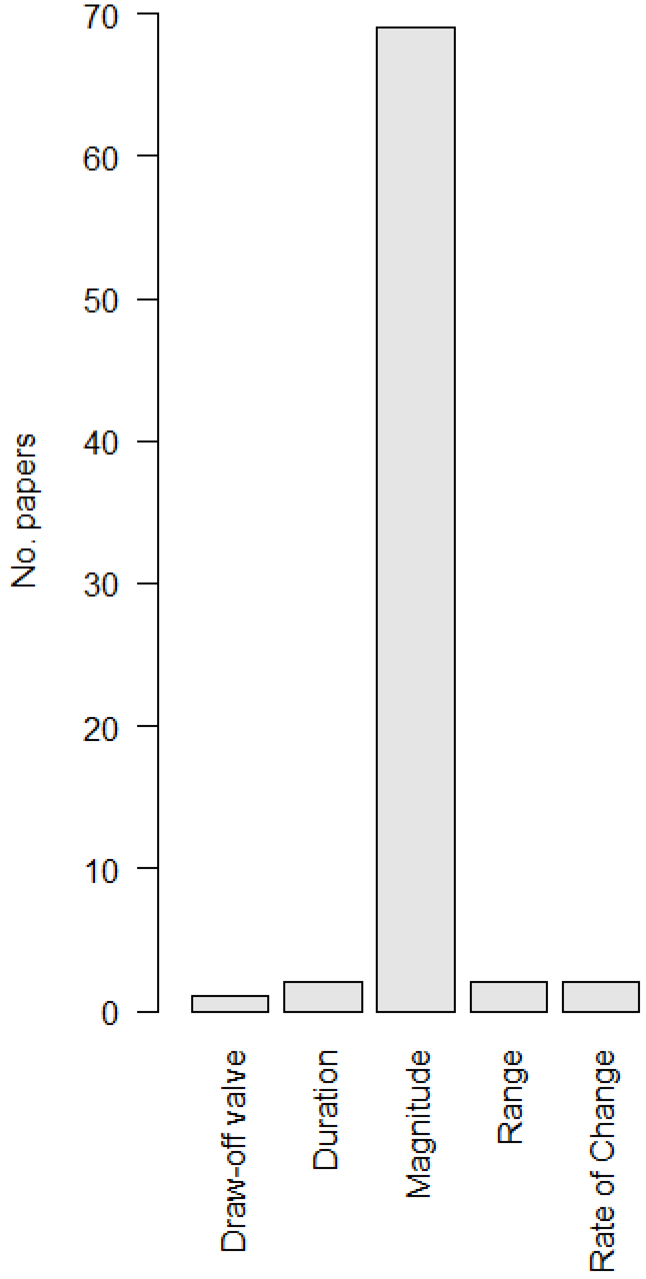

Figure 2 Number of studies (from a total of 76) that reported on each flow modification type.

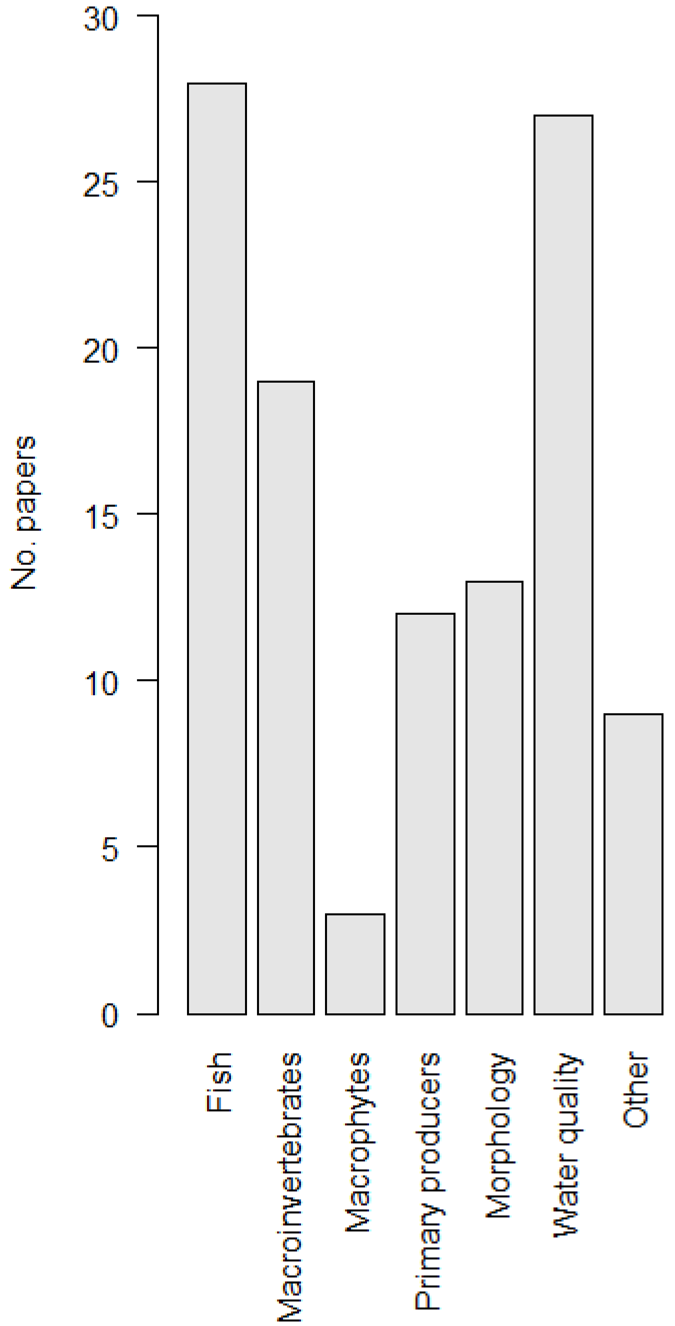

Figure 3 Number of studies (from a total of 76) that reported on each ecological response type. N.B. some studies reported on more than one category.

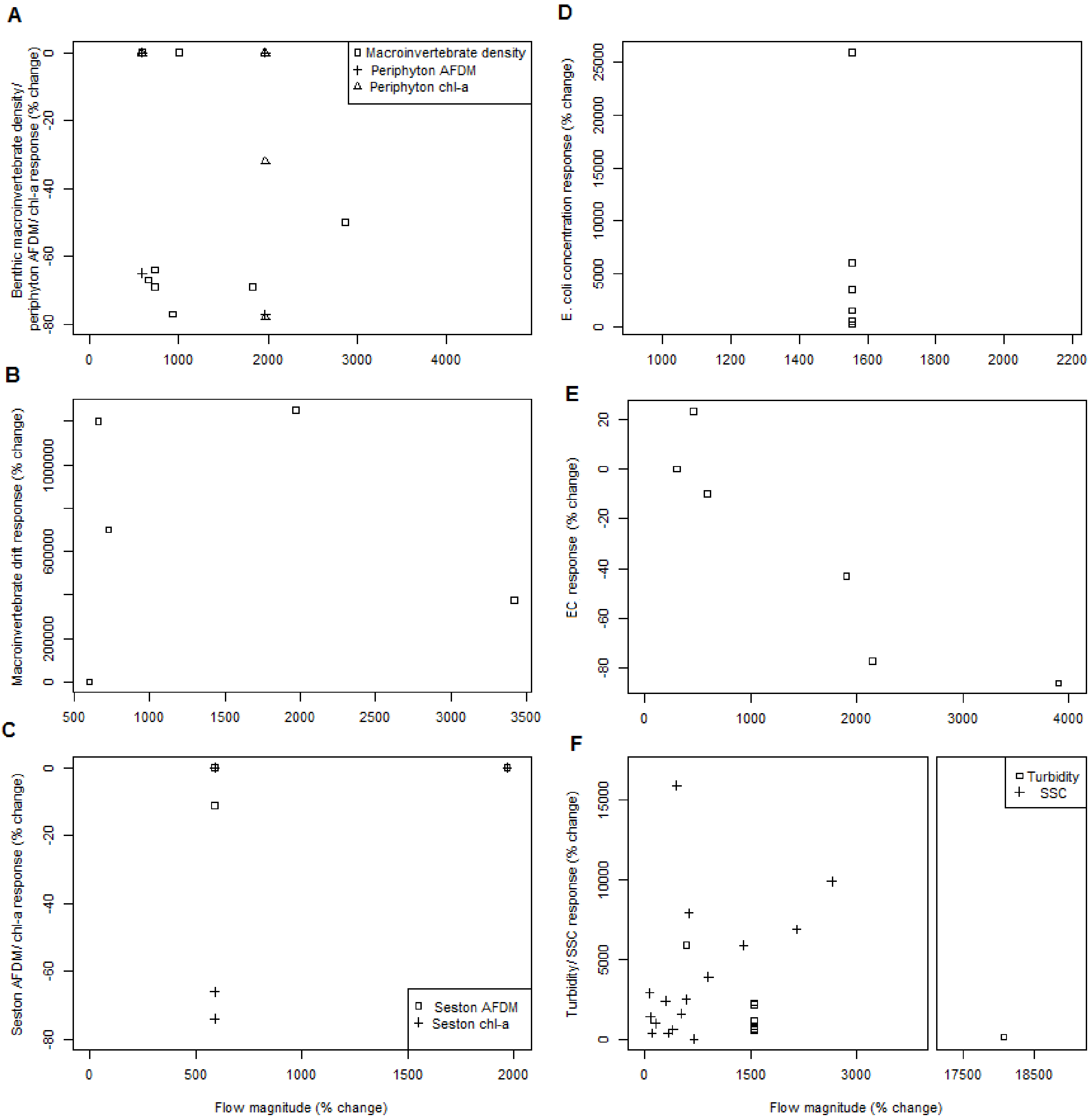

Figure 4 Biotic (A-D) and abiotic (E-F) ecological responses to flow magnitude percent change. N.B. Ecological responses are after- and during-flow modification for plots A-B and C-F, respectively.

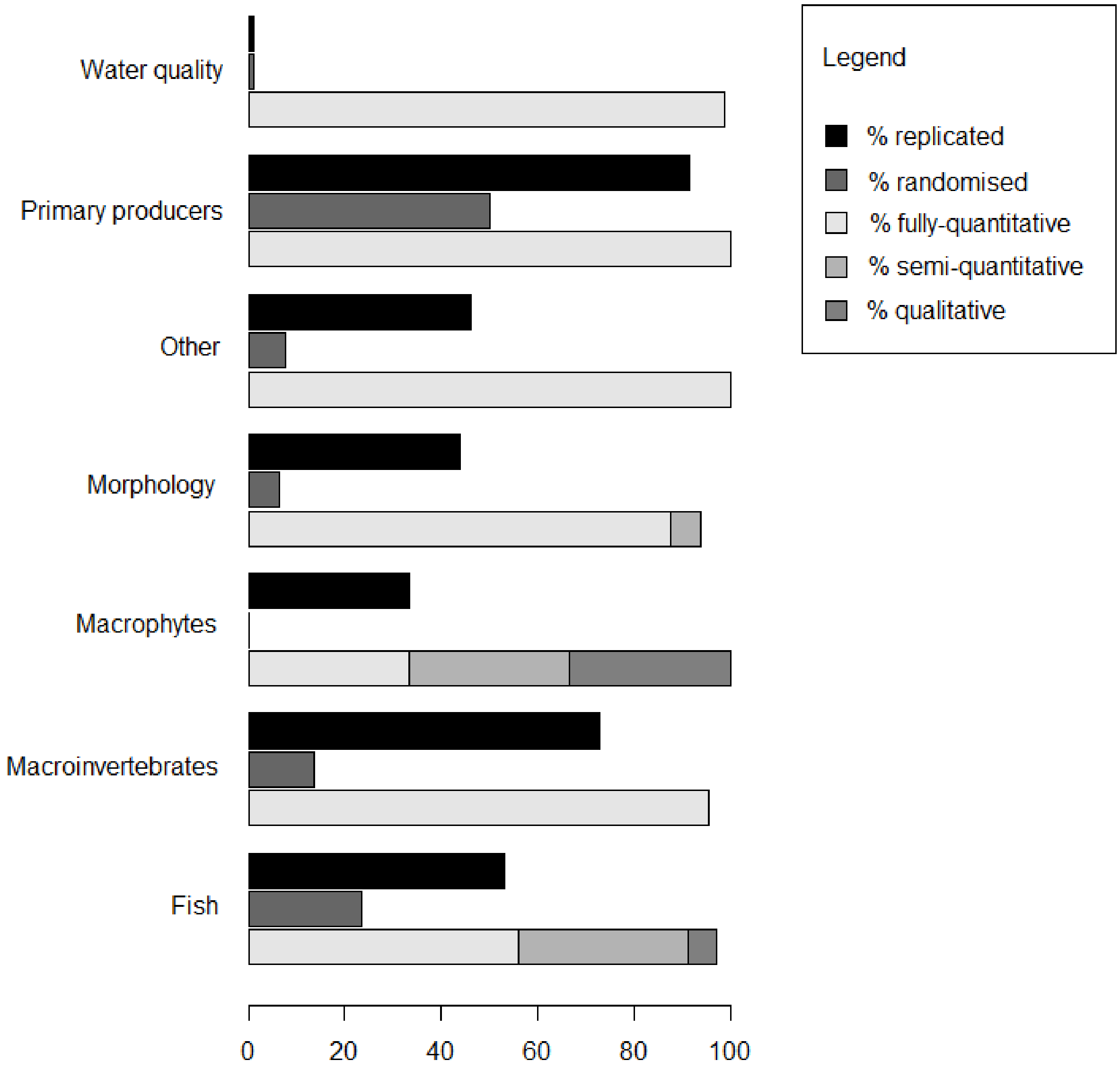

Figure 5 Bar plot of quality assessment indices for each ecosystem response. Note: percentages were calculated based on the total number of reported ecosystem responses; therefore, the sum of quantitative and qualitative percentages is less than 100 where quality assessment indices could not be extracted from a study

Tables

Table 1: Search terms used in literature search and respective number of results returned.

Search term	No. results
"reservoir operation"	825
effects AND hydropower	749
"selective withdrawal"	202
"reservoir release*"	200
"varying flows"	182
"pulse release*"	154
"controlled flood*"	129
"artificial flood*"	124
"dam operation"	124
"environmental flow*" AND dam	112
"experimental drought*"	110
"artificial flow*" NOT flower*	97
"flushing flow*"	93
"experimental flood*"	89
"hydropeaking"	83
"environmental flow*" AND reservoir	67
"dam release*"	65
"managed flood*"	56
"e-flows"	50
"artificial release*"	42
"flow alteration*" AND dam	42
"artificial drought"	40
"hydrop* flow*"	34
"planned flood*"	22
"altered flow* regime"	21
"flow alteration*" AND reservoir	21
"reservoir flushing"	20
"peaking flow*"	20
"scour* flow*"	18
"flood program"	18
"hydro-peaking"	17
"test flood*"	16
"hydropower peaking"	15
"environmental flow*" AND impoundment	14
"altered flow*" AND reservoir	11
"spate flow*" NOT flower*	10
"environmental release*" AND reservoir	10
"fluctuating flow*" AND dam	10
"peaking discharge*"	10
"flow alteration*" AND impoundment	9
"scour* flood"	8
"regulated flood"	8
"modified flow* regime"	7
"experimental low flow*"	7
"fluctuating flow*" AND reservoir	6
"dam reoperation"	3
"fluctuating flow*" AND impoundment	3
"spate flood*"	2
"dam re-operation*"	2
"environmental release*" AND dam	2
"reservoir reoperation"	1
"artificial low flow*"	1
"spate release*"	0
"scour* release*"	0
"reservoir re-operation"	0
"impoundment reoperation"	0
"impoundment re-operation"	0
"modified flow* AND reservoir"	0
"environmental release*" AND impoundment	0

Table 2: Total number of studies that reported on each flow modification type, number of studies that reported decreases, no changes or increases in biotic and abiotic ecological responses and most common ecological responses reported from a literature review of 76 studies. Where possible, reports are split between impacts of single (S) and cumulative (C) flow modifications. Study ID's are shown in parentheses (see Appendix 1 for study details).

			Biotic responses				**Abiotic responses**		
Flow modification type most emphasised by study (Poff & Zimmerman)		**Total no. studies**	**No. studies reporting reduced ecological responses**	**No. studies reporting no changes**	**No. studies reporting increased ecological responses**	**Common ecological responses**	**No. studies reporting change**	**No. studies reporting no change**	**Common ecological responses**
Magnitude	**S**	55	12	14	21	No change in fish movement (10,18,31,35,37,60,75) Increased fish movement (15,18,27,35,37,57) No change in fish abundance (13,65,72,75) Increased macroinvertebrate drift (17,20,42,43,48,62) Reduced macroinvertebrate density (34,48,61,63,54)	32	9	Increased turbidity (6,7,34,49) Increased suspended solids concentration (14,25,32,34,56,63,68,73) Reduced electrical conductivity (19,34,56,73) Increased bedload transport (12,24,36,55,59,66,68) No change in temperature (34,37,45,63) Increased temperature (18,22,37,42,51)
	C	21	14	9	10	Reduced macroinvertebrate density (20,29,43,45,63,64) Reduced periphyton mass (21,26,30,45,74)	4	0	n/a
Rate of change	**S**	2	1	1	1	n/a	0	0	n/a
Duration	**S**	2	1	0	1	n/a	1	0	
Draw-off depth	**S**	1	0	0	0	n/a	1	0	n/a
Range	**C**	2	1	1	2	n/a	0	0	n/a

Table 3: Conclusions drawn from this analysis of literature compared with those of Poff & Zimmerman (2010): ǂ - noted in both studies; ¥ - alternative noted in Poff & Zimmerman (2010); ¿ - not assessed by Poff & Zimmerman (2010). Recommendations for further research and literature analysis associated with conclusions drawn from this study are also noted where applicable.

Conclusions	**Recommendations**
Spatial distribution of studies	
Spatial bias identified (¿)	Prioritise areas where reservoir density is high and published research is currently limited
Flow and ecosystem response types	
Increased flow magnitude modification was main focus of studies (ǂ)	Diversify flow modification types assessed
	Assess impact of reduced flow magnitude
Generally, good variation in ecosystem response types assessed, but a bias towards traditionally monitored types was identified (e.g. fish; water quality) (¿)	Diversify ecosystem response types assessed
Qualitative flow-ecosystem response relationships	
Reservoir outflow modification has potential for use as management technique, but site-specific factors appear to be important (¿)	Focus on development of regional, or ecosystem 'type' based understanding rather than global scale (Poff & Zimmerman, 2010)
Long-term ecosystem response to both single- and cumulative- flow modifications unclear (¿)	Focus on long-term studies in a variety of locations (Poff & Zimmerman, 2010)
Abiotic responses: lack of monitoring post-flow modification (¿)	Focus on assessment of both during and post-flow modification
Quantitative flow-ecosystem response relationships	
Biotic ecosystem response: no clear trends identified (¥)	Conduct more studies to allow for site-specific factors to be accounted for in future reviews of quantitative flow-ecosystem response relationships
Abiotic ecosystem response: general linear flow modification: ecosystem response identified for EC and SSC, however, not statistically significant (¿)	
No threshold flows identified (ǂ)	
Limited number of data points restricted statistical analysis (ǂ)	Conduct more studies to enable both identification of trends and statistical analyses to be undertaken
Detail on potential confounding factors was not typically provided (ǂ)	Provide detail on potential confounding factors to enable robust modelling of flow-ecosystem response relationships
Quality assessment	
Majority of papers used fully-quantitative methods for at least one ecosystem response (¿)	
< 60% of assessments of fish or macrophytes were fully-quantitative (¿)	
> 60% of studies stated using replication, however only 25% stated using randomisation; this varied by ecosystem response type (¿)	Increase use of replication and randomisation, especially for assessment of water quality response
Analyses were typically simple one-way ANOVA which failed to take into account temporal autocorrelation (¿)	Use contemporary models to take autocorrelation into account where necessary
Few studies used control sites (¿)	Use control sites and BACI designs where appropriate
Both unregulated and regulated river types used as control sites (¿)	Assess the optimal control site 'type'
Few studies noted statistical power (¿)	Future research report statistical power
Inconsistent use of terminology within the literature (¿)	Use “reservoir” and “environmental flow” keyword terms where possible